Differential Astrometry of the 61 Cygni System with the Palomar Testbed Interferometer

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ABSTRACT

We present results of interferometric differential astrometric measurements of the nearby binary system 61 Cygni (HD 201091 and HD 201092) taken with the Palomar Testbed Interferometer in 1998 and 1999. After numerous hardware improvements implemented as a result of our 1998 experience, 1999 data on 61 Cyg exhibits astrometric precision of 100 microarcseconds (10^{-6} arcseconds, μas) over a one week time-scale, and 170 μas rms precision over a 70 day time-scale. Further, the 61 Cyg component differential proper motion measured by PTI in 1999 is in good agreement with the Hipparcos determination of system motion. A description of the PTI astrometric architecture, examples of PTI astrometric data, how it is collected, and the data processing to obtain our differential astrometric results on 61 Cyg are given.

1. Introduction

PTI is a long-baseline near-infrared interferometer located at Palomar Observatory (Colavita 1999). Chief among PTI's design features is the ability to track fringes simultaneously on two separate stars with the objective of performing precise differential astrometry; a concept first suggested by Shao and Colavita (1992). The primary objective of such differential astrometry is the detection of non-inertial stellar motions resulting from the gravitational influence of dim companions such as planets. To infer the presence of planetary-mass companions to nearby stars one must perform this differential astrometry at 10s of microarcsecond (10^{-6} arcseconds, μas) precision (see Black and Scargle 1982).

As a technology precursor for the Keck Interferometer (KI), PTI's primary design goal was the development and demonstration of dual-beam, interferometric differential astrometry at the 100 μas level. Here we give descriptions of PTI differential astrometric measurements on the nearby 30″ visual binary 61 Cygni (HD 201091 and HD 201092) from 1998 and 1999.

2. Measurements and Analysis Methodology

The interferometric observable used for these measurements is differential delay. The basic form of the interferometric astrometric equation is (e.g. Shao 1990):

$$d = \hat{\mathbf{s}} \cdot \mathbf{B} + C \tag{1}$$

where $\hat{\mathbf{s}}$ is a unit three-vector in the direction of the target star, B is the projected baseline three-vector, and C is a constant or *bias* term between true equilibrated optical path and that measured by a laser metrology system. Given two stars in directions $\hat{\mathbf{s}}_1$ and $\hat{\mathbf{s}}_2$, simultaneous fringe measurement on both stars with a common delay bias would measure a differential delay Δd as a proxy of the astrometric separation $\Delta\mathbf{s}$ (units of radians):

$$\Delta d \equiv d_2 - d_1 = \hat{\mathbf{s}}_2 \cdot \mathbf{B} + C - \hat{\mathbf{s}}_1 \cdot \mathbf{B} - C = \Delta\mathbf{s} \cdot \mathbf{B} \tag{2}$$

As a practical matter it is impossible to arrange a common delay bias among two separate paths. In this case, Δd as observed by our differential metrology signal is calibrated for the bias mismatch by subtracting a model bias mismatch $\widetilde{C_2} - \widetilde{C_1}$ estimated from simultaneous measurement of one of the stars with both beam combiners. In this construct a calibrated differential delay $\widetilde{\Delta d}$ becomes our proxy for the differential astrometric separation:

$$\widetilde{\Delta d} \equiv \Delta d - (\widetilde{C_2} - \widetilde{C_1}) \approx \Delta\mathbf{s} \cdot \mathbf{B} \tag{3}$$

External knowledge of $\mathbf{B}$ allows the estimate of a single projection of $\Delta\mathbf{s}$ from a single delay measurement. A ground based interferometer has this delay measurement corrupted by a random, zero-mean atmospheric delay fluctuation. Shao and Colavita (1992) and Colavita et al (1994) observed that over narrow fields these delay fluctuations are highly correlated, and are largely common mode in differential applications. However they are not perfectly correlated, and temporal averaging is required to refine the differential delay estimate to required accuracies for planet detection. Further, the fact that the baseline of an earth-based interferometer rotates with time means that both components of $\Delta\mathbf{s}$ can be extracted from a finite duration differential delay time series – with highly anisotropic errors (in a single-baseline measurement).

3. PTI Astrometry on 61 Cyg

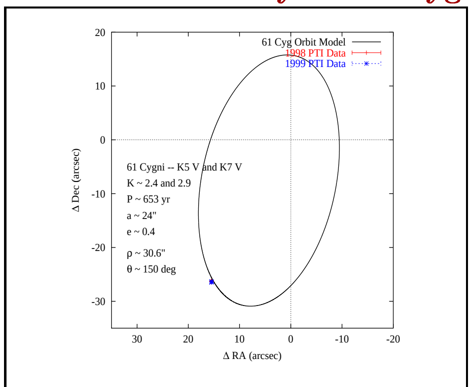

Fig. 1 61 Cyg Orbit Trace

PTI has used the nearby visual binary system 61 Cygni (HD 201091 and HD 201092 respectively) as its primary astrometric test target for the last three years. Figure 1 depicts the apparent visual orbit of the system along with our 1998 and 1999 astrometric observations; the system is currently near apoapsis. Table 1 summarizes PTI astrometric observations on 61 Cyg in 1998 and 1999.

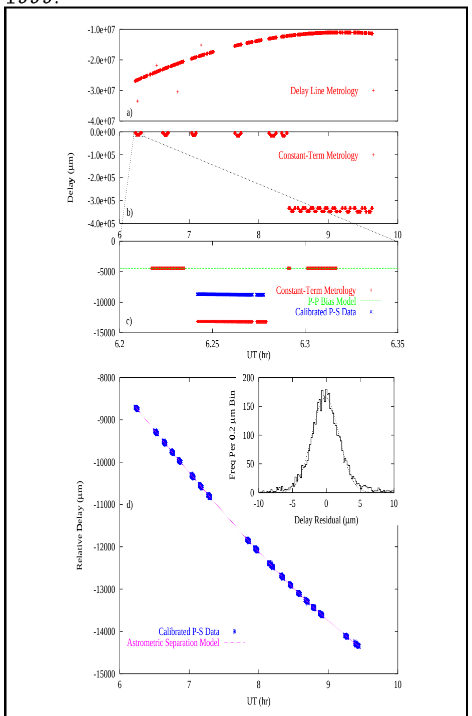

Fig. 2 Delay Calibration and Separation Estimation on a Night of PTI Astrometry Data.

Operationally we make astrometric measurements in so-called *triplets*; differential delay observations sandwiched between observations with both beam combiners on the same (*primary*) star. The primary-primary observations are used to estimate the time-varying differential bias value (discussed above), and subtracted from the differential delay measurements as per Eq. 3. These calibrated differential delays are then fit to obtain a separation estimate as discussed above. This process is depicted in Figure 2.

Table 1: PTI 61 Cygni Observation Summary

Year	# Nights	Begin Date	End Date
1998	18	216 (8/4)	270 (9/27)
1999	19	185 (7/4)	255 (9/12)

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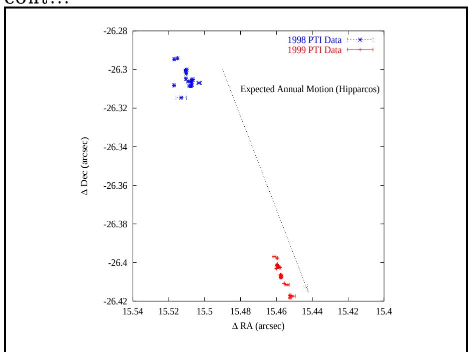

Fig. 3 1998 and 1999 PTI Astrometry on 61 Cyg.

Differential astrometric results from our 1998 and 1999 observations of 61 Cyg are summarized in Figures 3 and 4. Figure 3 gives a graphical depiction of both year's astrometry – the expected declination differential motion of roughly 120 mas/yr is evident at a gross level. While the quality of the 1998 astrometry is relatively crude, significant instrumental enhancements for the 1999 observing season resulted in much higher quality astrometry in 1999. In our principle declination measurement axis (PTI operates primarily as a N-S baseline) we see rms night-to-night repeatability under 200 μas over a two-month period, and better than 100 μas for a contiguous seven-night astrometry run in late July.

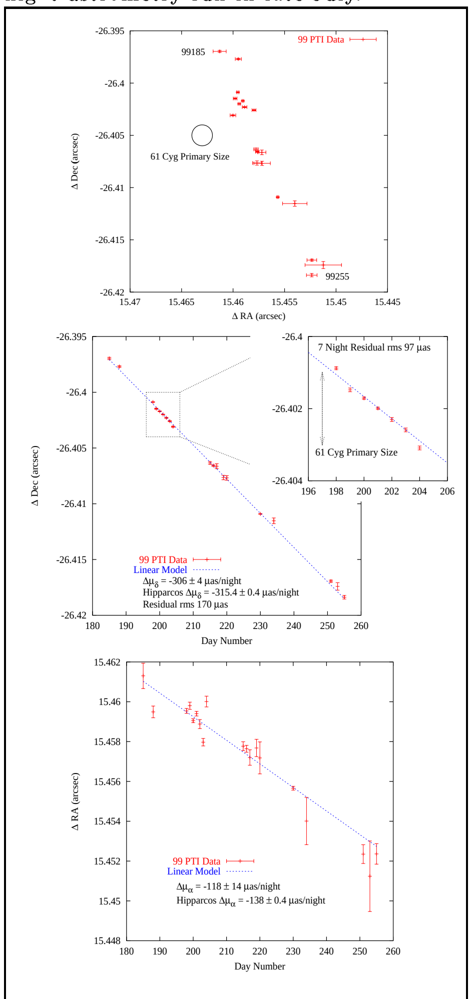

Fig. 4 1999 PTI Astrometry on 61 Cyg.

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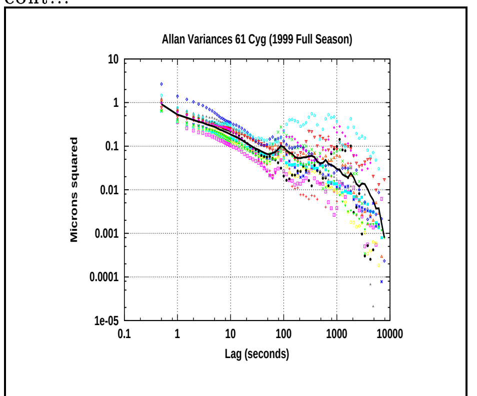

Fig. 5 Allan Variances From 1999 Separation Vector Delay Fit Residuals. 19 Individual Nights are Depicted, and the Average Behavior is Given in Heavy Black.

Allan variances computed from the residuals to separation fits in the 19 1999 astrometric nights are given in Figure 5. To make a 100 μas differential astrometric measurement PTI must measure the differential delay between the two stars to 0.055 μm; these Allan variance calculations indicate that atmospheric fluctuations in the differential delay measurement average down to these levels in roughly 1 hour of integration.

4. Discussion and Future Work

PTI's primary design goal was the demonstration of 100 μas-class interferometric differential astrometric measurements as a precursor to NASA's Keck Interferometer project (KI). With our observations in the 1999 observing season we have demonstrated 100 μas-class precision performance over a week time-scale, and sub-200 μas-class precision over a two month time-scale. Thus we feel we have achieved PTI's design goal and astrometric success criterion.

PTI astrometric measurements of 61 Cyg will continue in the 2000 observing season with the objective of establishing a three-year baseline for proper motion and relative parallax determination, and astrometric measurements using the quasi-orthogonal N-W baseline configuration to demonstrate similar 2d performance.

References:

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